

We Are Stardust ... Concentrated by Earth!

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The audacious aim of the emerging field of big history is to see all of the past as a unified field of study, combining insights from cosmology, astronomy, geology, paleontology, molecular evolution, paleoanthropology, archaeology, and all the fields of humanistic history, in order to achieve a whole new level of understanding of the human situation.

Big History: Between Nothing and Everything, by David Christian, Cynthia Stokes Brown, and Craig Benjamin (2013), is the first textbook for this new academic field. Having taught big history at Berkeley and seen the enormous enthusiasm it engenders in students who crave to see the world in broad perspective, I am pleased that we now have a book suitable for big history courses, but as a geologist, my (predictable!) complaint is that it could have told more about the fascinating history of Earth.

Although big history includes the regimes of Cosmos, Earth, Life, and Humanity, it is inherently anthropocentric, because we humans are doing the writing and because we know nothing about the histories that have unfolded on planets around other stars in this and other galaxies. The centrality of humans is clear from the Christian-Brown-Benjamin book, where human beings are the focus of three quarters of the book. As a result, the history of Earth, the only possible home for humans far into the foreseeable future, gets only a few pages. The information presented about our Earth—especially about the evolution of the atmosphere and about plate tectonics—is relevant and important to know, but it is just the beginning of the fascinating history of the earth that geologists have dug up.

A short time spent perusing the recent geological literature would probably convince you that geology is currently by far the greatest source of new historical information coming from any branch of big history, and it seems a shame for big historians not to be familiar with and excited about this treasure house of growing understanding.

In this essay, to convey the flavor of Earth history and its relevance to humanity, let me pick up on a point made strongly and correctly by Christian, Brown, and Benjamin—that almost all of the chemical elements important to humans were made in stars. And then let me show that this important point is incomplete, because it omits the role of Earth in concentrating those elements and making them useful.

We are stardust ...

The astronomer Carl Sagan brought science to life for large numbers of people in his 1980 television series *Cosmos*, which now looks like an early and very effective presentation of big history. Sagan was fond of saying that we are made of stardust. His point was that with the

exception of the three lightest—hydrogen, helium, and traces of lithium—all the chemical elements were cooked up inside stars, either slowly as by-products of the nuclear reactions that make the stars shine, or suddenly during supernovas, the great stellar explosions that scatter all the new elements into space. These chemical elements are the basis of the material world that is central to the human situation.

Humanistic big historians have picked up on this critical feature in the history of everything, stressing the great importance to us of the synthesis of elements inside stars. Christian, Brown and Benjamin select the synthesis of elements in stars as one of their eight thresholds in big history. But to a big historian like me, coming from a background in geology, Sagan's formulation is incomplete. The story does not end there, because chemical elements dispersed through interstellar space would be useless for building the world we know.

Imagine a long-range spaceship on its way to a distant solar system, and having an emergency need for silicon to fabricate computer chips. Although the ship is passing through the diffuse gas derived from old supernova explosions and that gas includes atoms of silicon, there would be no way for the astronauts to harvest and use the silicon.¹ The atoms are just too far apart.

... Made useful by Earth

But here on Earth it is easy. We have no trouble finding flint nodules, or sand on a beach, or crystals of quartz in a vein, all of them made of silicon bonded to oxygen—SiO₂. Clearly the role of Earth has been essential in making silicon useful to human beings. The point of this contribution is to explore how Earth does it, in the hope that big historians will amend Carl Sagan's idea that we are stardust, and recognize that, *We are stardust, made useful by Earth*.

We should start by recognizing that there have been two main phases in Earth's history of sorting chemical elements into useful concentrations. The first phase took place at the very beginning, as Earth was accreting. This phase gave us Earth's bulk composition, dominated by four elements—oxygen, magnesium, silicon and iron—with only small amounts of the other elements, but with all of them mixed up together.

The second phase has been going on ever since, with the progressive sorting out and concentrating of elements. Earth has many, many mechanisms for doing this work, so perhaps it is not surprising that big historians have focused on the conceptually simpler nucleosynthesis—the synthesis of elements—in the big bang and in stars. The present essay explores a few of Earth's sorting mechanisms, to give an idea of how Earth works its magic. The focus is on the element silicon, and on uses of silicon that are important in human history, so we might think of this as a “little big history” of silicon.²

A Focus on Silicon

The production of new elements inside stars that big historians appreciate so well is called stellar nucleosynthesis, and it lies in the domain of nuclear physics. The protons and neutrons in the

nuclei of atoms are bound so tightly by the strong nuclear force that wholesale changes can take place only at the extremely high temperatures and pressures in the cores of stars. On the other hand, the concentrating of elements inside Earth and at its surface takes place under much lower pressures and temperatures, which have no effect on the nuclei of atoms but allow all kinds of changes in how the atoms are bonded together, so this is in the realm of geochemistry.

If one had to identify the single most important discovery of geochemistry, it might be this: The solar system as a whole (like the universe as a whole) is fundamentally composed of a great deal of hydrogen, a moderate amount of helium, and only traces of all other elements, and this of course is the result of nucleosynthesis during the big bang and, later on, inside stars. But Earth, on the other hand, is dominantly composed of just four elements—oxygen, magnesium, silicon and iron (O, Mg, Si, Fe)—with traces of many other elements, among which the great components of the solar system, hydrogen and helium, are very minor. Somehow, Earth has selectively accumulated some of the rarer elements of the solar system. Let us see how this great geochemical discovery can be explained and how it affects our understanding of big history.

Of those four dominant elements, let's focus on silicon, first because it is the basis of most of the rocks that make up our planet and carry the record of Earth's history, and second because it has been critical to human activities for a very long time, as the raw material for crucial technologies like stone tools, glass, and computer chips.

Regarding the first point, it at first seems surprising that silicon is the basis of rocks while carbon is the basis of life. Carbon lies just above silicon in the periodic table, both make four chemical bonds with adjoining atoms, and this similarity has led science fiction writers to envision life based on silicon³, but that is not what happens. It turns out that carbon is a versatile element, bonding to hydrogen, oxygen, nitrogen, sulfur, and other carbon atoms, with both single and double bonds, easily changing the atoms to which it bonds, and this versatility makes it the perfect basis for the complex structures and dynamic processes of life. In contrast, silicon greatly prefers bonding to oxygen, making strong single bonds but no double bonds, and this is what is needed to make long-lasting minerals like the quartz (SiO_2) that is abundant in continental crust, and the olivine (Mg_2SiO_4) that dominates in the deep-earth mantle.

The minerals quartz and olivine, each with its characteristic formula, occur as grains that go together to make up rocks. A good analogy is that a rock is like a fruitcake, and minerals are like the fruit and nuts within the cake. Since solid minerals are quite resistant to change, so are the rocks made of minerals. Rocks generally record and remember aspects of the conditions under which they were deposited. Igneous rocks remember the temperature and pressure and chemistry of the molten magma from which they crystallized. Sedimentary rocks remember the processes that deposited them—rivers, wind, or glaciers. Metamorphic rocks remember the stresses that deformed them and the temperature and pressure under which they recrystallized into new minerals. Geologists have invented many ways of extracting this historical information from rocks and compiling it into an ever more sophisticated understanding of our planet's past. So we have a motto: *Ex libro lapidum historia mundi*—"Out of the book of rocks comes the history of the earth."

The second reason to focus on silicon is the critical role it has played in the rise of humanity to enormous technical prowess. The earliest human tools may have been made of wood, of which nothing remains, but the first tools of which we have a good record are made of silicon-based rocks. Moving from just the materials Nature gave us to artificial materials, a critical one has been glass, which basically comes from melting quartz. Finally, our modern, high-tech civilization is dependent on computer chips, which are made in sophisticated ways from silicon. Interestingly, Earth has concentrated the silicon used in each of these human artifacts in a different way.

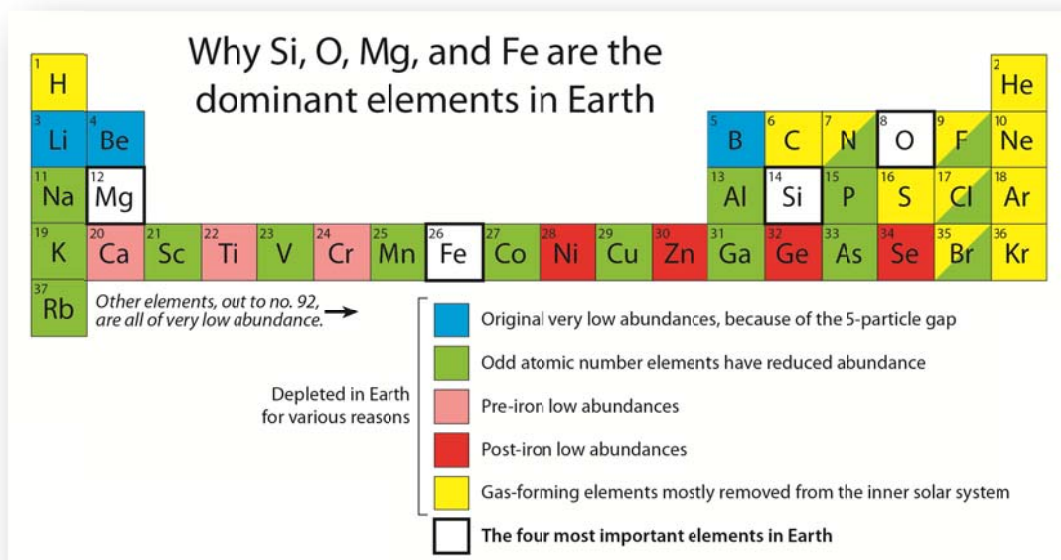
To see how Earth has concentrated silicon and made it useful, let us first look at the original accretion of the earth into a planet dominated by O, Mg, Si, and Fe, and then see how concentrations of Si have been formed on and within the earth.

How to Build an O-Mg-Si-Fe Planet

Returning to that major geochemical discovery—that the solar system is mostly made of hydrogen and helium while Earth is dominated by oxygen, magnesium, silicon, and iron—how can this be explained? What processes could account for this wholesale geochemical alteration?⁴

Evidently we are looking for processes that acted very early in the history of the solar system, because today there aren't any large amounts of material entering or leaving Earth, nor is there any sign of this happening in the four billion years for which we have a rock record. The occasional impact of an asteroid or comet, even a large one, is much too minor to change Earth's composition, and leakage off the top of the atmosphere to space affects only a few gaseous elements. At the beginning of the solar system, however, 4.567 billion years ago, Earth was growing rapidly, as objects from dust size to planet size accreted and stuck together. There were certainly opportunities during the formation of the earth for selecting some elements to accumulate in the earth, and excluding others.

In their textbook Christian, Brown, and Benjamin show a periodic table of the elements, marked up to indicate how and when the various elements were created, in the big bang and in stars. To supplement that figure, here is a partial periodic table that shows the fates of elements in the earth, singling out the big four:



A partial periodic table showing the fates of the elements during formation of the earth, stressing that our planet is mostly composed of oxygen, magnesium, silicon and iron. (Christian et al. 2013, 25).

Why were so many elements largely eliminated from Earth as it formed? Some elements (lithium, beryllium, boron, those with odd atomic numbers, and almost all the heavy elements) were simply too rare in the solar system ever to have had a chance of becoming important constituents of Earth. Other elements occur primarily as gases—that is, as single atoms, or as molecules made up of just a few atoms. These gaseous elements (hydrogen, helium, and the others shown in yellow in the figure) were swept out of Earth's habitat in the inner solar system to accumulate in the giant gas planets farther out—Jupiter, Saturn, Uranus and Neptune. The sweeping-out was done by powerful outflows of particles, mostly protons and electrons, driven out by the enormous energy released as all the material that would become the sun fell together. The outflow is called the T-Tauri wind, named after a very young star which is now in that condition. The present solar wind of our sun is but a faint memory of the violent outflow from the very early sun.

Which ones were *not* eliminated? Only mineral grains, each containing trillions of atoms, were massive enough to resist the pressure of the T-Tauri wind and stay in the inner solar system where Earth was forming. Silicon is what makes possible these large mineral grains, because it has four places where it can bond to another atom. Each of those bonds prefers to link to an oxygen, which can make two bonds, thus linking two silicon atoms together. So giant networks grow, each silicon surrounded by four oxygens, and each oxygen linking two silicons, with smaller amounts of other elements joining in—mostly magnesium and iron.

These networks are called silicate minerals, and they are the basis of pretty much all of the earth, except for the iron core. No matter how big a silicate mineral grain has grown, there are always silicon and oxygen atoms at the edge, waiting to grab onto more oxygens and silicons.

Silicate grains can thus become arbitrarily large, unless they are in an aggregate of grains—a rock—and run into another growing grain.

So the big-four elements—silicon, oxygen, magnesium, and iron—were all incorporated in the silicate minerals that make up the rocky part of Earth, with the leftover iron forming the metallic core. And thus it is silicon, whose four bonds make those minerals possible, that we can think of as Earth's favorite element.

Now let's go on and see how silicon, which was initially mixed up in our planet with oxygen, magnesium, iron, and some minor components, was sorted and concentrated by Earth into forms humans can use. That usage is quite amazing! A number of characteristics distinguish humans from all other animals, and among those features are complex tools, artificial materials, and computers. *Tools* let us do things our natural hands and bodies cannot do, *artificial materials* let us do things impossible with natural materials, and *computers* let us do things our natural brains cannot do.

In the rest of this contribution we will look at one example from each of those three categories—stone tools, glass, and computer chips. Each is based on silicon, which is not just one of Earth's favorite elements, but one of ours as well. Conveniently, each of those technologies uses silicon that was concentrated in a different way, so we can get some feeling for the variety of remarkable processes through which Earth has produced the mineral deposits we depend on.

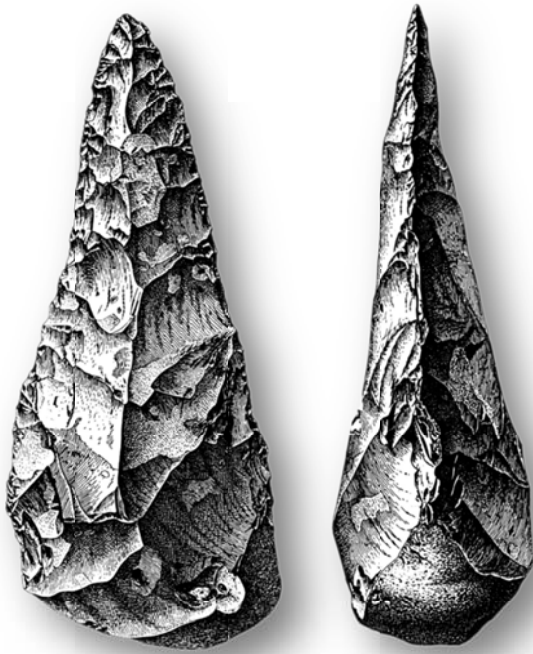
Silicon and stone tools

Think of the variety of tools we use! From simple knives, hammers, saws and screwdrivers, to more complicated tools like violins and pianos, drill presses, agricultural harvesting machines, and industrial looms, to really sophisticated, high-tech tools like interplanetary spacecraft, laser ranging devices, global-positioning-system receivers, and computer-controlled three-dimensional printers—the list is almost endless and portrays a species with a technological virtuosity that would have been inconceivable even a million years ago. Primates have been seen to use and sometimes make very simple tools, and some birds and invertebrates may use found objects as primitive tools, but the complexity of tool manufacture and use by human beings is quite unique.

How and when did this virtuosity begin? We are unlikely ever to find examples of objects at the transition from found objects to purposely-constructed tools, because wood, the most likely material, is so perishable. But the record for stone tools is abundant. Archaeologists, who like to divide history into three parts, have long divided the human past into three ages—Stone Age, Bronze Age, and Iron Age—based on the kinds of tools found in excavations.

The earliest recognized stone tools are found in East Africa, dating from about 2.5 million years ago, and seem to have been made by *Homo habilis*, whose species name reflects this tool-making ability. These are simply pebbles with random chips knocked off, giving sharp edges that could be used for cutting. They have been called the Oldowan Industry, after Olduvai Gorge in Tanzania. Subsequent stone-tool industries, like the Acheulean hand axes, display increasing

sophistication on the part of the tool makers, with some tools so skillfully and beautifully made that they qualify as works of art as well as practical objects. It seems very probable that human brains and tool-making abilities increased together in a kind of feedback loop over the last 2.5 million years.



*An Acheulean hand axe made of flint, from the original locality of Saint-Acheul, in France.
(Image from Wikimedia Commons:
http://commons.wikimedia.org/wiki/File:Biface_silex.png)*

What made all of this possible is that some rocks, when broken, give very hard, sharp edges, which has allowed us humans, with our blunt teeth and soft fingernails, to match and exceed the cutting abilities of the animals with the sharpest teeth and claws.

Nick Toth and Kathy Shick, paleoanthropologists who study stone tools and who founded the Stone Age Institute at Indiana University, are among the pioneers of big history.⁵ They are skilled makers and users of stone tools, and it is a remarkable experience to watch one of them produce an Acheulean hand axe, for example—the main tool used by *Homo erectus*, between about 1.5 and half a million years ago. They point out that stone tools allowed the vegetarian early humans to start eating energy-rich meat when we did not have the teeth or claws to do it naturally. Stone tools gave us the ability to hunt animals larger than we are, and to keep away carnivores who were interested in eating us.



Nick Toth considers where to strike off the next flake while making a hand axe. (Photo by the author.)

Most rocks do not break with sharp edges, or are too soft to hold a cutting edge, so one could never make a useful tool from sandstone, limestone, granite, gypsum, or rock salt. The two best materials for tool making are the volcanic glass called obsidian, and the sedimentary rock called chert, or flint. Obsidian is rich in SiO_2 , but is rare, so let us concentrate on chert, which is almost perfectly pure SiO_2 and is not so rare. What is chert, and how does it come to have this very special composition? Or—to pick up the theme of this essay—how did Earth concentrate the SiO_2 in chert?

Chert commonly occurs as nodules in limestone. Both are sedimentary rocks of biological origin. Limestone is made of the mineral calcite (CaCO_3), while chert is extremely fine-grained quartz (SiO_2). It is clear from the mineral hardness scale, arranged from softest to hardest (talc, gypsum, *calcite*, fluorite, apatite, orthoclase, *quartz*, topaz, corundum, diamond), that chert will make better tools than limestone.

Most marine organisms make their shells from CaCO_3 extracted from seawater, while just a few extract SiO_2 —sponges and the single-celled radiolarians are the most important. Most freshly deposited limestone contains a small amount of dispersed SiO_2 , but it can be dissolved by pore water and then concentrated and precipitated in chemically favorable levels, producing beds or nodules of chert, which were greatly prized by our ancestors who made stone tools.

The famous Stone Age monument of Stonehenge, in southern England, was built and improved over about 800 years in a place where high-quality chert nodules were particularly abundant. Stonehenge helps us realize that silicon was as critical an element in Stone Age times as it is today, and perhaps we could think of Stonehenge as the first Silicon Valley.

All of this history of manufacture and use of stone tools made from chert, and its probable role in our expanding brains and growing intelligence, was made possible because Earth has biological and then chemical mechanisms for separating silica from the other major elements—iron and magnesium—and from all the other minor elements in our planet, and forming beautiful chert nodules of pure SiO_2 from which tools can be made.

Silicon and the manufacture of glass

Chert is not the only material for making stone tools with sharp, hard edges—they have also been made from obsidian, a natural glass of volcanic origin. Obsidian forms when molten rock cools so rapidly that there is no time for crystals to grow. Although humans have long used naturally occurring glass, eventually they learned to make artificial glass themselves. Glass technology seems to have begun around 3500 BCE in Mesopotamia or Egypt, about the same time and place people learned to make bronze by mixing copper and tin. So glass and bronze appear to mark the beginning of a history in which humans have learned to make and use an ever more varied array of remarkable artificial materials.

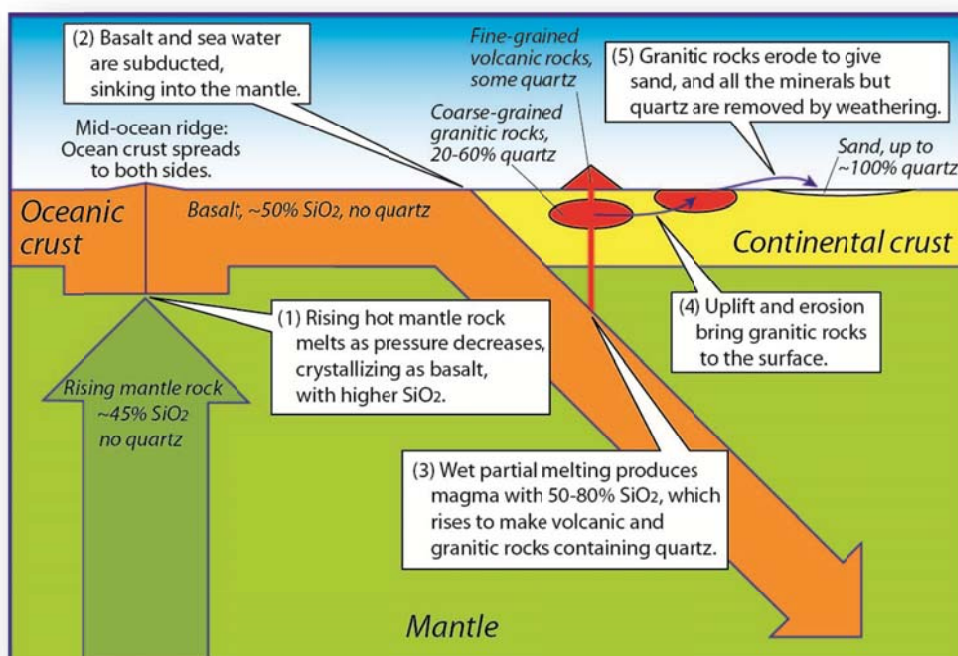
Think for a moment about what glass does for us. Glass windows allow us to have light inside our houses, cars, and airplanes during the day, and light bulbs illuminate them at night. Glass gives us waterproof pitchers, bottles and drinking glasses, and it allows us to see in mirrors and through corrective lenses. In telescopes, microscopes and myriad other scientific devices it has allowed us to understand our world. It insulates high-voltage power lines, provides fiber-optic cables, and gives us monitors and touch screens for computers. In mosaics and stained-glass windows it has been a medium for great art.

Almost all glass made today is based on melting and then rapidly cooling silica, SiO_2 , with smaller amounts of other elements added to give it desirable properties. The point here is not the details of how glass is made, but rather the question how Earth has concentrated the silica we use for glass manufacture. This will lead us deeper into understanding Earth's virtuosic ability to separate and concentrate chemical elements, because the silica used in glass making was concentrated in a completely different way from the silica used for making stone tools. Fortunately we are not dependent on chert nodules to make glass, for chert is not so abundant. On the contrary, there are enormous supplies of silica in that most common of geological deposits—plain old sand.

Most sand is composed largely or almost entirely of little grains of quartz, and is familiar to anyone who ever walks on a beach or through the dunes. But it is surprising at first, when you think about how Earth concentrates elements, because during the original accretion of Earth there was no mechanism to produce quartz. As we have seen, there were mechanisms to eliminate

most of the elements in the newly-formed Earth except for iron, magnesium, silicon, and oxygen. With abundant Si and O, you might think that lots of quartz, SiO_2 , would have formed, but that is not the case. Instead, there was so much Fe and Mg around that all the Si and O were combined with Fe and Mg to make silicate minerals other than quartz. In fact, to first approximation, Earth is made of (1) an iron core and (2) a mantle with the composition of the mineral olivine, Mg_2SiO_4 . So where did all the present-day quartz sand come from?

Here we meet one of the most fascinating features of Earth's geochemical evolution. For 4.5 billion years it has acted as a giant chemical processing plant that has slowly, gradually extracted quartz from rocks that contained silica but no quartz. Here, in a very simplified summary, are the steps Earth uses to work this chemical magic:



A simplified cartoon showing the steps by which Earth converts quartz-free mantle rock into the nearly pure quartz sand we use to make glass.

First, the hot olivine-rich mantle rock called peridotite rises beneath the mid-ocean ridges, and partially melts as the pressure decreases. The lower-density portion, richer in SiO_2 though still with no quartz, forms the basalt of the ocean crust, which spreads laterally in both directions as the ocean basin expands.

Second, after tens or hundreds of millions of years, the basaltic ocean crust, now cold and dense, subducts—sinks back down into the mantle.

Third, in a process that is still not fully understood, water carried down along with the basalt causes partial melting in the subducting slab or above it, and silica is further concentrated in the melt. The molten rock rises and either erupts in great chains of volcanoes like those of Japan, the

Andes, and the Cascades of Washington and Oregon, or cools slowly at depth to form coarse-grained granitic rocks as we see in the Sierra Nevada of California. The volcanic rocks may contain some crystals of quartz, and the granitic rocks are rich in coarse grains of quartz.

Fourth, uplift and erosion eventually bring the granitic rocks to the surface. Earth has almost finished the job, but the quartz in the granitic rocks is mixed with other minerals, especially feldspar. It is time to purify the quartz.



Yosemite: a sea of granitic rocks, uplifted and eroding, giving quartz-rich sand (Photo by Starlingjon at en.wikipedia).

Up to this point, all of the silica enrichment has taken place at high temperatures inside the earth through magmatic processes that concentrate silica in the melt and leave silica-poor residues behind. The fifth and final step is completely different, involving chemical weathering at Earth's surface—the same mechanism that produces soil. During weathering, the feldspar and other minerals in granite decay and are converted to clay, especially in hot, wet climates, because they are not stable chemically at the earth's surface. Clay minerals occur as very tiny grains, which are easily carried away by water and wind, leaving the quartz behind. The grains of quartz are extremely stable and endure pretty much forever, accumulating in sand dunes, river channels, and beaches, that may be nearly pure quartz. Earth has completed the job, and in many places around the world these great sand deposits are quarried for the quartz used to make glass.⁶

A sand grain's story

The accumulation of quartz sand on the earth's surface can involve intricate and fascinating stories. One example is a remarkable discovery by William Dickinson and George Gehrels of the University of Arizona (Dickinson and Gehrels 2009). Anyone who has visited the Colorado Plateau of southeastern Utah will remember the great cliffs of Arches and Canyonlands National Parks, marking thick sheets of ancient sand that was deposited as dunes, in a former landscape much like the modern Sahara Desert. Sloping layers in the sandstone mark ancient faces of dunes, telling the wind direction when they were deposited, so geologists have long known that the ancient wind was blowing dominantly from the north and that the sand grains in these dunes were blown from Wyoming south to Utah.

Almost all of the sand grains in these ancient dune deposits are quartz, but a very small fraction of the grains are the mineral zircon. Like quartz, zircon is very resistant to chemical alteration, so it lasts indefinitely, but unlike quartz, zircon can be dated, because it contains a little uranium which decays radioactively to lead. This in turn gives the age of the granitic source rocks from which the zircon grains, as well as the quartz, were derived. Dickinson and Gehrels dated more than 1600 zircon grains from sandstones of the Colorado Plateau, and to their surprise the ages did not correspond to any source rocks in Wyoming, or to any known rocks in western North America. The only source rocks of the right age are in the eastern United States, in the Appalachian Mountains!

But how could quartz from the Appalachians get into sand dunes on the Colorado Plateau? It could not happen today, because sand carried westward from the Appalachians by rivers would end up in the Mississippi and then be carried to the Gulf of Mexico. Prior to that, in the Cretaceous, the interior of North America was submerged by a wide, shallow sea, and sand grains reaching that sea would stay there, on the sea floor. But in the Jurassic, about 150–200 million years ago, the situation was different, as Dickinson and Gehrels pointed out. Rather than the present geography, with the low Appalachian Mountains in the east, the Mississippi River, in the middle, and the high Rocky Mountains in the west, Jurassic North America had a long, gradual, gentle slope from high topography in the east, uplifted because Africa was rifting away from North America, gradually descending to sea level where the Rocky Mountains are now. Before there ever was a Mississippi, a great west-flowing river, whose exact route we can only guess, must have carried vast numbers of Appalachian sand grains all the way to the shoreline in Wyoming, and from there they were blown by the wind to their final resting place in Utah. Who would have imagined, while gazing at a sandstone cliff in Utah, that they were seeing the Appalachian Mountains, disassembled and carried 2,000 miles across the continent by a long-vanished river?

The ability to reconstruct a great river of long ago, of which every trace has been removed by erosion, is an example of the wonderful historical discoveries that geologists are contributing to big history. And it gives a hint of the array of remarkable processes and surprising episodes by

which Earth has concentrated the kinds of valuable materials that has made human civilization and technology possible.

Silicon and computers

In the early twenty-first century we live in a new silicon age, in which this element, the critical ingredient for our Earth itself and once the basis for Stone Age tools, is now again of critical importance, as the foundation for the computer chips that pervade almost every aspect of our lives, our technology, and our civilization. The ancient Silicon Valley of Stonehenge has been replaced by the new Silicon Valley in California, and similar centers of high technology elsewhere.

How has Earth concentrated the silicon used for computer chips? Curiously, this has happened by a process completely different from those that have concentrated the silicon used in stone tools and in glass, and this helps us appreciate the range of Earth's geochemical skills.

At the earth's surface, SiO_2 is extremely insoluble in water, which is why those grains of quartz sand last indefinitely. But that is not the case deep in the earth, where water chemistry is different and the temperatures are much higher. Under those conditions, SiO_2 can be dissolved out of the abundant silicate minerals of the crust, carried upward by the hot, silica-rich waters as they rise, and deposited in open fractures near the surface when conditions have reached the point where silica is no longer soluble. Fractures filled with SiO_2 are called quartz veins, and they are very abundant in areas that once had hot rocks at depth, resulting in hydrothermal, or hot-water, circulation.

The exquisite quartz crystals and the beautiful clusters of purple amethyst crystals, also quartz, on display in rock shops were deposited by hot water in open fractures that became quartz veins, with the perfect pyramidal crystal terminations formed as the crystal grew into an open cavity filled with silica-rich water that came up from depth.

Quartz veins have long been of extreme economic importance, because gold, if present at depth, gets carried along with SiO_2 in hydrothermal systems and deposited in veins near the surface. Many of the world's great gold-producing regions have this origin, including the deposits of northwestern Spain that supplied the gold of the Roman Empire, and the Sierra Nevada foothills of California, where the richest gold concentrations are in a great system of quartz veins called the Mother Lode.

Now, however, because of the great purity of SiO_2 in quartz veins, these have become the preferred source of silicon metal, refined from the quartz, which is the basis for making computer chips. Of course the process of converting quartz crystals into silicon metal and adding just the right impurities is extremely complex and difficult, but again the point here is that Earth has concentrated the silica in a most interesting way. Perhaps we should conclude that technology is the result of human ingenuity, building on Earth's ingenuity.

The Lesson for Big Historians

Recognizing Earth's three different ways of accumulating the silica we use for making stone tools, glass, and computer chips barely scratches the surface of the rich array of mechanisms by which our planet has produced the concentrations of the elements we use. Almost every chemical element gets enriched by Earth in one or more ways. Hydrogen and oxygen end up in the ocean water; oxygen and nitrogen in the atmosphere; sodium, potassium and chlorine in evaporated salt deposits; iron in the deposits of ancient seas whose geochemistry was unlike those of today: copper in hydrothermal vent chimneys on the mid-ocean spreading ridges; uranium in ancient river channels; calcium in limestones; carbon in limestone, coal, and hydrocarbons.

Perhaps it is the enormous variety of these different mechanisms and the subtle geochemistry some of them involve that has kept them unfamiliar to most people. But surely big historians need to recognize that Carl Sagan's wonderful insight—that we are made of stardust—is incomplete without also understanding that our planet has done the complicated, sophisticated job of separating that stardust into its constituent elements, which makes them useful for constructing rocks, animals, plants, human beings, and our technological world.

Endnotes

1. Three terms used in this essay may at first be confusing: “Silicon” means element 14, Si. “Silica” is the combination SiO_2 , which is the formula of the mineral quartz. “Silicate” refers to a mineral containing silicon and oxygen, such as olivine (Mg_2SiO_4), with a structure based on the “silicate tetrahedron”—a single small silicon atom surrounded by four large oxygen atoms in a tetrahedral arrangement. In addition, “silicone” is a synthetic material made of silicon, oxygen, carbon, and hydrogen; it is not an Earth material and does not enter our story.
2. Big history is a vast topic, so Fred Spier has suggested the writing of “little big histories,” exploring all the history that lies behind some feature of our world. So there could be little big histories of cats, of a language, or of silicon, as in this essay.
3. An example of the silicon-based-life concept is the *Star Trek* episode, “The Devil in the Dark.”
4. This question is answered in detail in an excellent little book: Broecker 1988, 291.
5. Nick and Kathy's remarkable Big History museum exhibit, *From the Big Bang to the World Wide Web*, is available online at <http://www.bigbangtowww.org/>

6. A huge quarry in Illinois that extracts Ordovician sand, for use in glass making, from deposits about 455–460 million years old, can be seen on *Bing Maps* or *Google Earth* at 41° 20.529' N, 88° 52.636' W.

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